

Spin wave resonances in antiferromagnets

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Spin wave resonances with enormously large wave numbers corresponding to wave vectors $k \sim 10^5 \div 10^6 \text{ cm}^{-1}$ are observed in thin plates of FeBO_3 . The study of spin wave resonances allows one to obtain information about the spin wave spectrum. The temperature dependence of a non-uniform exchange constant is determined for FeBO_3 . Considerable softening of the magnon spectrum resulting from the interaction of magnons, is observed at temperatures above $1/3$ of the Néel temperature. The excitation level of spin wave resonances is found to depend significantly on the inhomogeneous elastic distortions artificially created in the sample. A theoretical model to describe the observed effects is proposed.

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I. INTRODUCTION

The linear excitation of spin waves in an ideal infinite crystal is possible only if the frequency of pumping field ω_p matches the spin-wave frequency ω_k (the law of conservation of energy) and their wave vectors are equal (the law of conservation of quasi-momentum). Since the wave vector of a microwave field is relatively small ($\leq 10^2 \text{ cm}^{-1}$) the spin waves with large wave vectors cannot be excited.

The presence of defects in a sample allows the law of conservation of quasi-momentum to be broken and makes the linear excitation possible. One kind of possible natural defects in magnets is given by the sample edges. If the magnon free path is comparable to the sample size, the magnetic excitation spectrum becomes discrete, giving rise to a finite coupling of the uniform microwave field with spin-wave modes of the sample with non-zero wave numbers.

For a plane-parallel plate, the microwave field can be coupled to the modes with $k_{\parallel} = 0$ and $k_{\perp} \neq 0$, *i.e.* with oscillations of magnetization which are uniform in-plane and non-uniform across the plate. The excitation of such oscillations (standing spin waves) by a uniform microwave magnetic field (referred to as a spin-wave resonance) was predicted by Kittel¹ and proven experimentally.² The resonance-field values are determined not only by the bulk properties of a magnet but also by the fixation of the magnetic moments on its surface. The boundary conditions for spins fully fixed on a crystal surface are determined by the following relation:

$$k_{zn} = n\pi/d. \quad (1)$$

Only modes with odd number of half-periods are coupled to the microwave magnetic field, with the efficiency of this coupling decreasing inversely proportional to the wave vector k_z . The study of spin-wave resonances in ferro- and ferrimagnetic films allows one to obtain information about non-uniform exchange constants and surface properties of magnets.³

This work describes the experimental investigation of the linear excitation of spin-wave resonances with large wave numbers $k \sim 10^5 \div 10^6 \text{ cm}^{-1}$ in a single crystal of the easy-plane antiferromagnet FeBO_3 .

The static and dynamic properties of the rhombohedral antiferromagnet FeBO_3 (symmetry group D_{3d}^6 , Néel temperature $T_N = 348 \text{ K}$) with an easy-plane anisotropy are studied in detail.⁴ The low frequency branch of the spin-wave spectrum at static magnetic field $H \perp C_3$ is given by the relation:

$$\omega_{1,k}^2 = \gamma^2 [H(H + H_D) + H_{\Delta}^2 + \alpha_{\perp}^2 k_{\perp}^2 + \alpha_{\parallel}^2 k_{\parallel}^2], \quad (2)$$

where γ is the gyromagnetic ratio, H_D is the Dzyaloshinsky field, H_{Δ} is a parameter determined by magnetoelastic coupling, H is the external field applied in the basal plane of the crystal, α_{\parallel} and α_{\perp} are non-uniform exchange constants, k_{\parallel} and k_{\perp} are wave-vector components along the C_3 -axis and in the basal plane respectively. The values of these constants at $T = 77 \text{ K}$ are the following: $\gamma = 2\pi \cdot 2.8 \text{ GHz/kOe}$, $H_D \simeq 100 \text{ kOe}$, $H_{\Delta} \simeq 1.9 \text{ kOe}$, $\alpha_{\parallel} = 7.8 \cdot 10^{-2} \text{ Oe}\cdot\text{cm}$.⁴

The observability of parametric excitation of spin waves shows that the lifetime of magnons with the frequency $\omega_k/2\pi \simeq 10^{10} \text{ Hz}$ and wave vector $\mathbf{k} = 0 \div 10^6 \text{ cm}^{-1}$ is rather long at helium temperatures: $\tau \sim 0.1 \div 1 \text{ }\mu\text{sec}$. The velocity of magnons with $\mathbf{k} = 10^5 - 10^6 \text{ cm}^{-1}$ is $s_k = |\partial\omega_k/\partial k| \sim 10^5 - 10^6 \text{ cm/sec}$. Using these values one can estimate the magnon free path $\lambda = s\tau \simeq 1 \text{ mm}$. Therefore, samples with the thickness smaller than 0.1 mm should be used to observe spin-wave resonances.

II. SAMPLES AND EXPERIMENTAL TECHNIQUE

Single crystal plates with the size of approximately $0.02 \times 3 \times 4 \text{ mm}^3$ were used in our experiments. Their developed faces coincided with the basal plane and were optically smooth. The sample quality was checked by x-ray

topography. Only homogeneous single-domain samples were chosen for the measurements.

The investigations were carried out using a standard Q-band Bruker spectrometer. The field derivative of the transmitted signal dP/dH was measured as a function of external magnetic field H . The measurements were performed in the temperature range 4.2 to 280 K.

III. SPIN WAVE RESONANCES IN UNDISTORTED FeBO_3 SAMPLES

The experiment was done on a single-crystal plate of $d = 0.02$ mm in thickness at a frequency $\omega_p/2\pi = 34.4$ GHz. Since the resonance absorption in FeBO_3 was found to depend on the way of sample mounting, we used the most delicate one. The thin-walled glass tube was filled by chemically pure fine powder of sodium chloride. The sample was put horizontally and covered by salt to prevent it from motion. The tube was inserted into the resonator. This mounting procedure minimizes the sample deformation which can be checked by the antiferromagnetic resonance (AFMR) linewidth. The upper panel of Fig. 1 shows the AFMR line records taken at various temperatures. The external magnetic field \mathbf{H} and the microwave field \mathbf{h} are mutually perpendicular and lie in the basal plane of the crystal. On increasing the temperature, the line shifts to larger fields. The temperature dependence of the resonance field H_0 is represented on the lower panel of Fig. 1. The AFMR linewidth is $\Delta H = 12 \pm 1$ Oe in the whole temperature range. At $T < 30$ K the line becomes asymmetric.

The field dependences of derivatives of the transmitted signal dP/dH taken at various temperatures are presented in Fig. 2. Regular absorption lines are observed on these records, with their positions shifting to larger fields on heating, analogously to the AFMR lines. The sensitivity of the spectrometer does not depend on the temperature of the record. Several most pronounced lines were traced in a wide temperature range. The corresponding dependences of four resonance fields are shown on the lower panel of Fig. 1. Spin-wave resonances with large wave vectors were observed up to temperatures ~ 250 K. The spin-wave resonances start to decrease in amplitude below $T \sim 50$ K and become practically unresolvable at $T \lesssim 30$ K. The linewidth of a single spin-wave resonance is ≈ 6 Oe in the vicinity of H_0 and ≈ 10 Oe in low fields.

The fragment of the record $dP/dH(H)$ at $T = 100$ K is shown on the lower panel of Fig. 2. The distance between neighboring spin-wave resonance fields calculated by formula (2) is marked by a segment. One can see that spin-wave resonances with both odd and even wave numbers are excited.

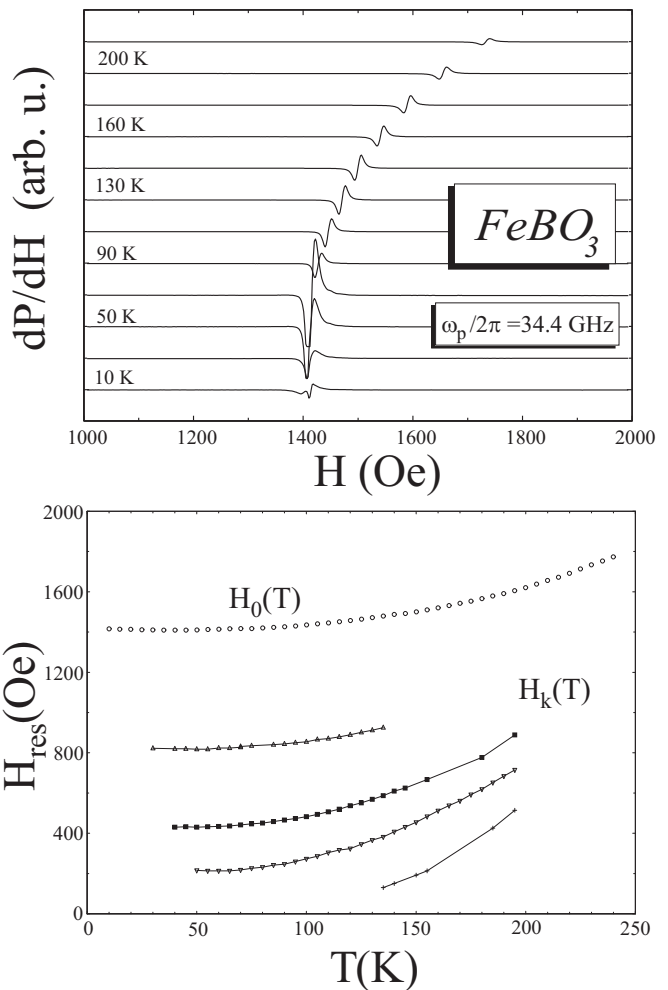


FIG. 1: Upper panel: the field dependence of derivatives of the transmitted signal dP/dH recorded at various temperatures. Lower panel: the temperature dependences of an antiferromagnetic resonance and four spin-wave resonance fields traced in a wide temperature range (corresponding records are shown in Fig. 2); the absorption lines at various temperatures are rescaled and shifted.

IV. SPIN WAVE RESONANCES IN FeBO_3 SAMPLES WITH INHOMOGENEOUS DISTORTIONS

Our samples were thin plates with their thickness being at least 100 times smaller than the other dimensions. Application of a glue onto one of the developed sample planes creates a tension which is non-uniform across the plate: the sample is compressed from one side and stretched from the other (see insert in Fig. 4). Since the thermal expansion coefficients of the glue and the sample are different, the value of the tension depends on temperature. Narrow resonance lines are observed on the background of a broadened AFMR line, becoming denser and more intense in the vicinity of the resonance field H_0 . This fine structure is especially pronounced around 100 K

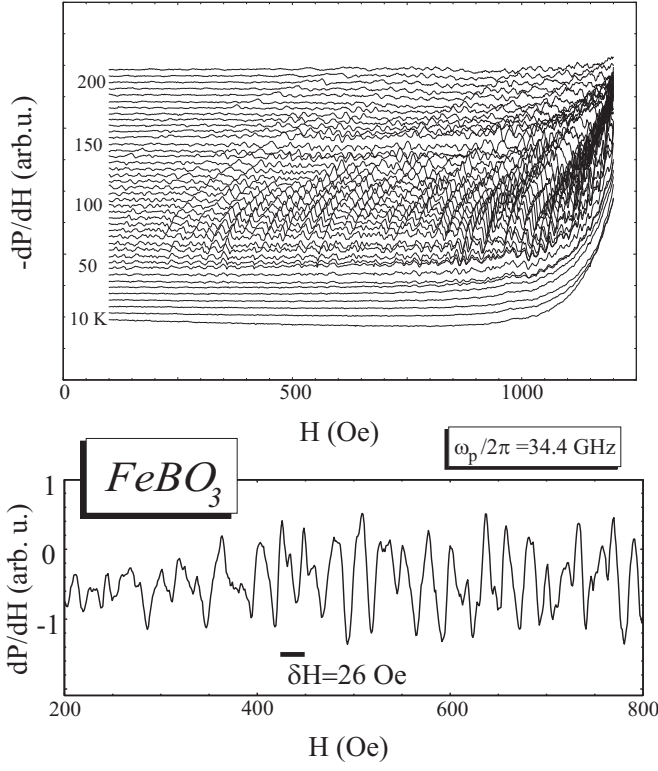


FIG. 2: The field records of derivatives of the transmitted signal at various temperatures.

and disappears below 30 K.

Fig.3 shows a fragment of the AFMR line recorded at $T = 80$ K. The positions of the spin-wave resonances calculated by formula (2) with the above values of constants and $k_z = \pi n/d$ (the plate thickness $d = 0.016$ mm) are given on the upper scale of this Figure. The field intervals between the neighboring resonance features are in good agreement with these calculations. The spin-wave resonances observed in the low-field range correspond to numbers $n \simeq 80$, i.e. $k_z \simeq 1.5 \cdot 10^5 \text{ cm}^{-1}$. The spin-wave resonances with $n \leq 20 - 30$ in the vicinity of H_0 are not resolved. The modes with odd and even number of half-periods n are excited in the vicinity of an AFMR field with roughly the same efficiency, while apart from H_0 each other resonance was considerably weaker. The intensity of the spin-wave resonances in a sample with inhomogeneous distortion is at least by two orders of magnitude larger than that in an undistorted sample.

The influence of uniaxial stress on the spin-wave spectrum in easy-plane antiferromagnets was studied both experimentally and theoretically.⁵⁻⁷ It was shown that the effect of uniaxial stress \mathbf{p} in the basal plane of the crystal can be described by an effective magnetic field $\mathbf{H}_{me}(\mathbf{p})$. The additional gap $H_{\Delta 1}^2$ arising in the spin-wave spectrum is related to this field by the following expression:

$$H_{\Delta 1}^2 = 2H_E H_{me}(p), \quad (3)$$

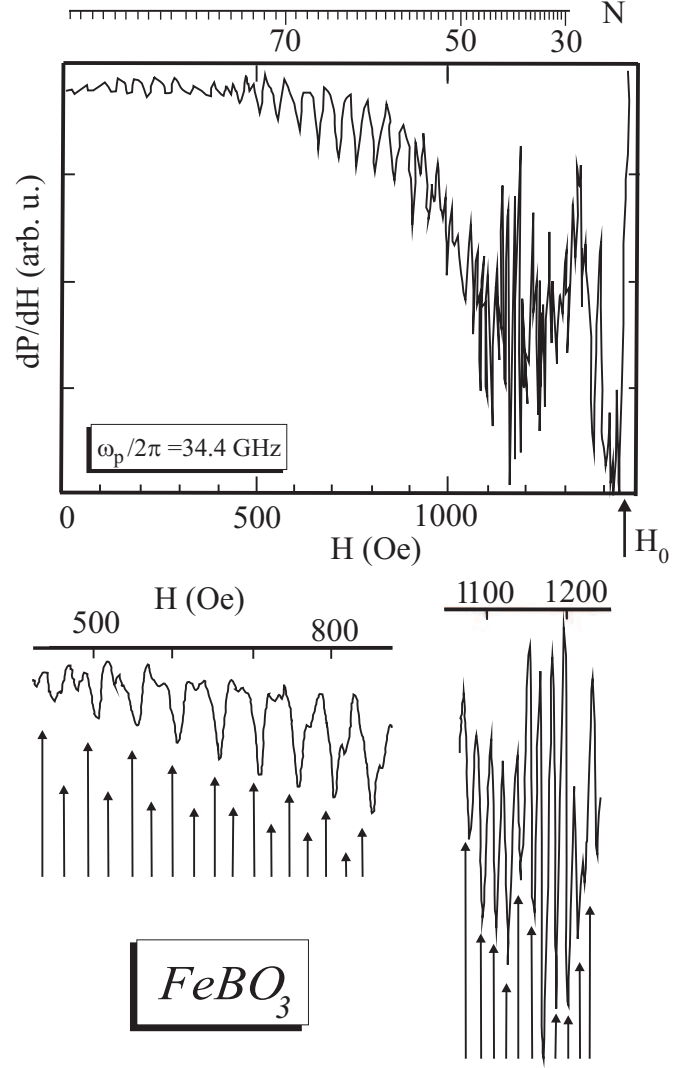


FIG. 3: Fragment of the derivative of the transmitted signal dP/dH measured at $T = 80$ K in the sample with one of the sides covered by a thin film of glue. The positions of spin-wave resonances with the wave number $k_z = \pi n/d$ ($d = 0.016$ mm is the plate thickness) obtained by formulae (1,2) are given on the upper scale. The lower panel shows two expanded fragments of this record. The calculated resonance field values are marked by arrows.

where H_E is the exchange field. Thus, even weak distortions can significantly modify the spin wave spectrum in such antiferromagnets due to “exchange amplification”. In case of a uniaxial distortion, the magnetoelastic gap changes across the plate, so that the wave vector of a spin wave propagating perpendicular to the basal plane should depend on z -coordinate.

Let us discuss how the spin-wave resonances change in the presence of such distortions. The spin-wave resonance condition can be expressed as follows:³

$$\int_0^d k(z, p, H) dz = \pi n, \quad (4)$$

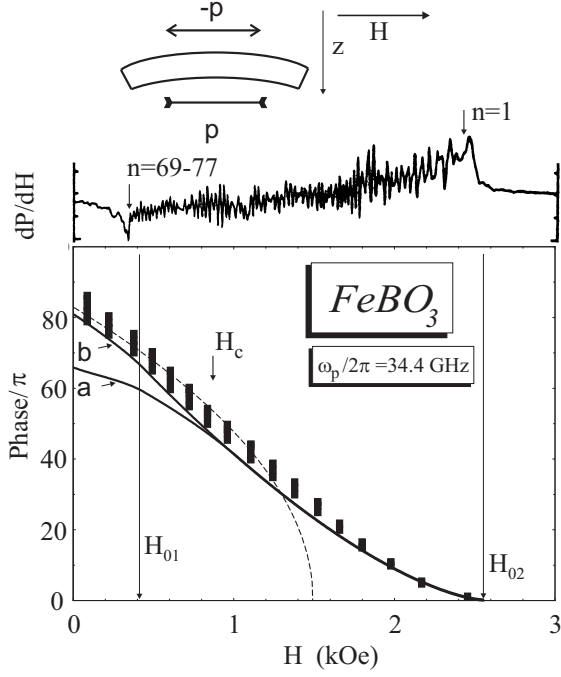


FIG. 4: Upper panel: Calculated field dependences $n(H) = \text{Phase}/\pi = \int_0^d k(z)dz/\pi$ (solid lines a,b). Spin-wave resonances are expected near fields at which the phase is divisible by π . The curve ‘a’ is calculated taking into account the rotation of an antiferromagnetic vector at fields $H < H_c$ and under the condition $\mathbf{p} \parallel \mathbf{H}$; the curve ‘b’ is calculated under the condition $\mathbf{l} \perp \mathbf{H}$ in the whole sample at all fields H . The calculated $n(H)$ dependence for an undistorted sample is shown by the dashed line. Black rectangles correspond to the $n(H)$ dependence obtained from the experimental curve shown on the upper panel of the Figure; $T = 80$ K, $d = 0.013$ mm, $\omega_p/2\pi = 34.4$ GHz.

where n is an integer determining the number of the spin-wave resonance. This equation is written under the assumption that the spins are fully fixed at sample edges. Supposing that the value of a uniaxial stress varies linearly from $-p$ to p , one can calculate the spin-wave resonance fields for a given plate thickness and compare them to the experiment. The value of an uncontrollable parameter p can be estimated by the position of the features observed on the field dependences of dP/dH at $H = H_{01}$ and $H = H_{02}$ (see the experimental curve on the upper panel of Fig. 4). We relate these features to fields at which the condition $\omega_p \simeq \omega(k \simeq 0, H)$ is satisfied in the vicinity of upper and lower edges of the crystal. The calculated field dependences of $\text{Phase}/\pi = \int_0^d k(z)dz/\pi$ are shown on the lower panel of Fig. 4 by solid lines a,b. The spin-wave resonances are expected around the field at which the phase is divisible by π . The experimentally obtained spin-wave resonance numbers n at some fields H are shown on the same Figure by black rectangles. The height of the rectangle corresponds to the error in experimental determination of n . The experimental $n(H)$ dependence is well described by the proposed model. In

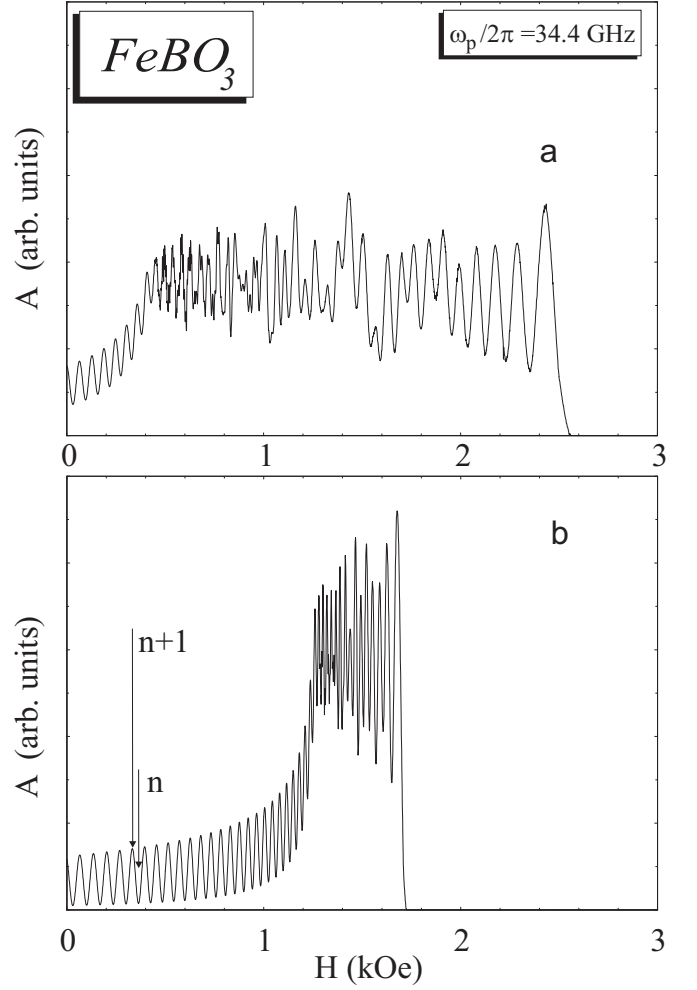


FIG. 5: Calculated field dependencies of a coupling coefficient of spin wave resonances with a uniform microwave field for two values of non-uniform distortions. Panel ‘a’ corresponds to the same value of p as in Fig. 4 at $H_c = 200$ Oe, the value of p on panel ‘b’ corresponds to Fig. 3 at $H_c = 100$ Oe.

the low field range the function $n(H)$ strongly depends on the angle between the vectors \mathbf{p} and \mathbf{H} . The observed discrepancy between the experiment and model curve ‘a’ at low fields is possibly associated with unparallel orientation of these vectors.

Fig. 5 shows the calculated field dependencies of a coupling coefficient $A(H)$ of spin wave resonances with a uniform microwave field for two values of non-uniform distortions. Panel ‘a’ shows the calculation with the same parameter p as in Fig. 4, while that on panel ‘b’ is the same as in Fig. 3. This coefficient is calculated as follows:

$$A(p, H) = A_0 \int_0^d \sin\left(\int_0^z k(z, p, H)dz\right)dz. \quad (5)$$

One can see that the spin wave resonances with both odd and even wave numbers are coupled to the microwave field due to non-uniform distortion of the sample. The amplitudes of spin wave resonances calculated

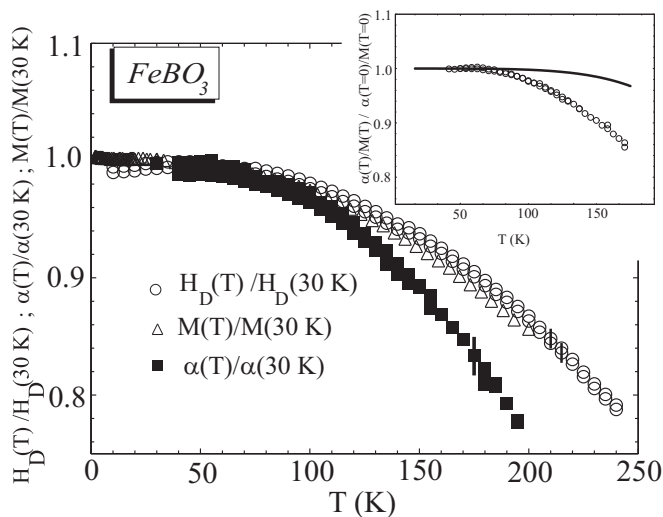


FIG. 6: Temperature dependencies of a Dzyaloshinsky field $H_D(T)$ (○) determined from AFMR measurements, a non-uniform exchange constant $\alpha(T)$ (■) and magnetic moment of FeBO_3 sample in a field $H = 1.5$ kOe applied in the basal plane of the crystal (△). All dependencies are rescaled to values of corresponding parameters measured at $T = 30$ K. The inset shows the correction to the non-uniform-exchange constant α/M due to interaction of magnons calculated in⁸, and the same ratio obtained from the experimental results shown on the Figure.

in the frame of the discussed model are irregular at fields $H_{c1} < H < H_{c2}$ and regular in the low field range. Thus, the above model is in satisfactory agreement with experimentally observed spectra.

V. CONCLUSION

In conclusion, the spin wave resonances with $k \approx 1.5 \cdot 10^5 \text{ cm}^{-1}$ are observed in single-crystal plates of FeBO_3 . The fact, that the spin-wave resonances observed in samples with non-uniform distortions are at least 100 times more intensive than those in undistorted ones demonstrates the influence of an elastic tension on the coupling of a standing spin wave with microwave field. Besides, the non-uniform distortion inevitably leads to

the coupling between the microwave pumping and resonances both with odd and even wave numbers n (see Fig. 5). The spin wave resonances with even n were also observed in undistorted samples which probably results from internal tensions in these crystals.

Spin-wave resonances were clearly observed in the temperature interval $30 \div 250$ K. The resonance line can be recorded, if its linewidth is smaller than the distance between neighboring lines. The upper temperature limit is determined by enhanced damping of spin waves due to three magnon processes.⁴ The lowest boundary is stipulated by the proximity to the damping peak at $T = 18$ K resulting from the “low relaxation” process due to Fe^{2+} impurities in FeBO_3 crystals.⁴ Since the spin-wave resonances are well resolved in a wide temperature range, one can trace the temperature dependence of the resonance field for resonances with large wave numbers. The corresponding data for several wave numbers are given on the lower panel of Fig. 6. Assuming the spin-wave spectrum in the whole temperature interval to be described by formula (2), one can obtain the temperature dependence of the non-uniform exchange constant $\alpha_{||}(T)$.

Fig. 6 demonstrates the temperature dependences $\alpha_{||}(T)$ and $H_D(T)$. As seen from this Figure, the $H_D(T)$ dependence coincides within the experimental accuracy with the dependence of a spontaneous magnetic moment $M(T)$ measured in the same sample by standard SQUID-magnetometer. The value of the non-uniform exchange constant $\alpha_{||}$ at $T > 100$ K decreases considerably faster on increasing the temperature. The effect of three- and four magnon interaction processes on the magnon spectrum in an easy-plane antiferromagnet was studied earlier.⁸ The upper panel of Fig. 6 shows the correction to the exchange constant α/M . The calculated decrease of the exchange constant is about 5 times smaller than that experimentally found at $T = 150$ K. The observed discrepancy can be associated with the assumption made in Ref. 8 that the low magnon branch is gapless ($H = 0$, $H_\Delta^2 = 0$).

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